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EFFECT OF GRAIN REFINEMENT ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF 4340M

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23

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MICROSTRUCTURE AND MECHANICAL PROPERTIES OF 4340M

Donald Webster

INTRODUCTION

Previous papers (1,2) have described a technique for refining the austenite grain of a high-strength stainless steel, AFC 77, and the resultant improvement in mechanical properties. The technique, which is thought to involve the formation of deformation voids around hard carbide particles (1), can be employed on a wide variety of steels. The present work describes the grain refinement obtained in a high-strength, low-alloy steel, 4340M, and its effect on the mechanical properties of that steel.

MATERIAL

The 4340M used in this study was received as a 2-1/4-in.-square billet. Composition by weight percent of the vacuum-melted steel (as reported by the manufacturer) is as follows:

C	Mn	Si	S	P	Ni	Cr	Mo	V
0.43	0.84	1.72	0.004	0.010	1.72	0.77	0.39	0.08

EXPERIMENTAL PROCEDURE

HEAT TREATMENT

The 2-1/4-in.-square billet was hot rolled at 2100°F to 1.12-in.-thick plate. Material for specimens of coarse grain size was then further hot rolled to 0.56-in.-thick plate (normal heat treatment). Material for specimens to be used for evaluating the austenite grain refining technique was tempered at 1275°F for 1 hr and then cold rolled 50% to 0.56-in.-thick plate, with two intermediate anneals at 1275°F. A final austenitizing treatment of 1/2 hr at temperatures

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between 1500°F and 1600°F was carried out in vacuum. These specimens were then oil quenched and tempered at 400°F or 550°F for 2 + 2 hr. Specimens removed at various temperatures for microstructural examination from material given either heat treatment were water quenched.

MECHANICAL TESTS

Tension Tests

Tension tests were conducted at room temperature on 0.25-in.-dia specimens tested at a strain rate of 0.005 in./in./min through yield and then loaded at a crosshead speed of 0.100 in./min to failure.

Fracture Toughness Tests

Fracture toughness tests were carried out on single-edge-notched specimens 7.5 by 1.5 by 0.5 in. tested in three-point bending.

Stress-Corrosion Tests

Stress-corrosion testing under plane-strain conditions was conducted on fatigue precracked single-edge-notched bend specimens tested in cantilever bending (3). Testing was carried out in a 3.5% NaCl solution, with fresh solution constantly dripping into the upturned notch. The crack was immersed in the solution before the load was applied. Specimens were held 1 week at each stress-intensity level before unloading. Crack growth rate under plane-strain conditions was calculated by dividing the length of the crack by the total time elapsed since the initial loading. Since incubation period is ignored, rate of crack growth is plotted as an apparent crack growth rate. Rate of crack growth is zero at K_{Iscc}.

METALLOGRAPHY

Austenite grain size was determined by measuring the mean linear intercept of 200 grains. For grain sizes below 20 μ , measurement was made on carbon replicas examined in the electron microscope.

RESULTS AND DISCUSSION

GRAIN REFINEMENT

At temperatures just below Ac_1, both deformed (Fig. 1) and undeformed specimens consist of partially recrystallized tempered martensite. The recrystallized ferrite grains tend to be coarser and more equiaxed in the deformed material. At the Ac_1 temperature, the morphology of the austenite that begins to form in the deformed and undeformed specimens is markedly different. Austenite formed in the undeformed material is acicular and similar in morphology to the tempered martensite from which it forms (Figs. 2 and 3). Carbides at the austenite-martensite interface can be seen to be exerting some degree of pinning that will have the effect of stabilizing what is basically an unstable structure. Examination of the structure at a lower magnification with the scanning electron microscope reveals that there is a high degree of alignment of the undissolved ferrite lathes within each prior austenite grain (Fig. 4). At some temperature between Ac_1 and Ac_3, the small acicular austenite grains grow rapidly until the new grain size is the same as that of the prior austenite grain size, and the new austenite grain boundaries lie between the differently aligned groups of ferrite lathes (Fig. 5).

In marked contrast, the newly formed austenite in the deformed material exists as fine ($\sim 1\,\mu$) equiaxed grains, and the undissolved ferrite is present in almost equiaxed blocks along the austenite grain boundaries (Fig. 6). With increasing austenitizing temperature, the residual ferrite dissolves and a small amount of grain growth occurs, until at 1500°F the structure consists entirely of fine-grained austenite and undissolved carbides that are probably V_4C_3. At 1525°F these carbides are still undissolved (Fig. 7), but at 1550°F are almost completely in solution (Fig. 8). A schematic representation of the microstructural changes that occur during the austenitizing of deformed and undeformed martensite is shown in Fig. 9.

The effect of austenitizing temperature on the austenite grain size of deformed and undeformed 4340M is shown in Fig. 10. The anomalously coarse grain size produced in the region of 1500°F in the undeformed material is commonly observed in low-alloy steels containing vanadium (4) and is thought to be due to the preferential unpinning of austenite grain boundaries that occurs during the gradual solution of vanadium carbide in the range 1450° to 1500°F. The specimens treated at 1550°F and 1600°F were heated rapidly through the critical range so that all the grain boundaries were released at the same time and discontinuous grain growth was prevented. However, in large components, in which slow heating ($<$ 500°F/hr) is unavoidable, grain growth occurs in the critical range and a coarse grain size is obtained at all heat-treatment temperatures. In deformed material, a fine grain size is maintained even at slow heating rates.

MECHANICAL PROPERTIES

Tensile and Fracture Toughness Properties

Grain refinement results in an increase in strength and toughness in material tempered at 400°F (Fig. 11) and at 550°F (Fig. 12). This increase is most noticeable at an austenitizing temperature of 1500°F, where the effect of grain size is most marked. As in most cases of grain refinement, the yield strength is increased more than the ultimate strength.

The optimum strength of 4340M is obtained at about 1550°F. At lower temperatures, undissolved vanadium carbides remain which lower the carbon content of the matrix and hence the strength. At higher temperatures, grain coarsening occurs which also reduces strength. Grain refinement results in improvement in both strength and toughness at 1500°F, but at 1550°F the grain size difference is too small to produce a measurable difference in the mechanical properties. To achive optimum mechanical properties with maximum grain refinement in 4340M would require alloying to either lower the Ac_3 temperature or raise the temperature at which significant grain refinement is achieved.

Stress-Corrosion Properties

The apparent crack growth rates in 3.5% NaCl solution for fine- and coarse-grained specimens are shown in Fig. 13. The threshold lies between 12 and 15 ksi $\sqrt{in.}$ and does not seem to be markedly affected by either grain size or tempering temperature. The fracture path in both fine- and coarse-grained specimens is predominantly intergranular (Fig. 14).

CONCLUSIONS

1. Deformation of tempered martensite in 4340M steel results in a marked reduction in austenite grain size at austenitizing temperatures between Ac_1 and 50°F above Ac_3.

2. This grain refinement results in a modest increase in strength and toughness but no increase in stress-corrosion threshold (K_{Iscc}) after the austenitizing temperature of 1500°F. At higher austenitizing temperatures, there is little effect on either grain size or mechanical properties.

3. Slow heating produces an increase in austenite grain size in undeformed material by allowing discontinuous grain growth to occur. Slow heating does not coarsen the austenite grain size of deformed material.

4. To achieve the optimum benefit from the grain refinement process studied, it is necessary to design a steel for which the austenitizing temperature for optimum mechanical properties is coincident with the temperature of maximum grain refinement. In the case of 4340M, this would mean alloying to either lower the Ac_3 temperature or raise the temperature at which significant grain refinement is achieved.

ACKNOWLEDGMENTS

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Figure 1 4340M: tempered 1 hr at 1275°F, cold reduced 70%, tempered 1 hr at 1250°F, and water quenched. Partially recrystallized tempered martensite shows duplex recrystallized grains. Thin foil (X60,000).

Figure 2 4340M: undeformed tempered martensite austenitized 1 hr at 1325°F and water quenched. Acicular, newly formed austenite is marked A in background of recrystallized ferrite. Undissolved carbides are pinning the phase boundaries. Extraction replica (X30,000).

Figure 3 4340M: undeformed tempered martensite austenitized 1 hr at 1380°F and water quenched. Acicular untempered martensite and recrystallized ferrite. At 1380°F the martensitic areas were austenitic. Thin foil (X72,000).

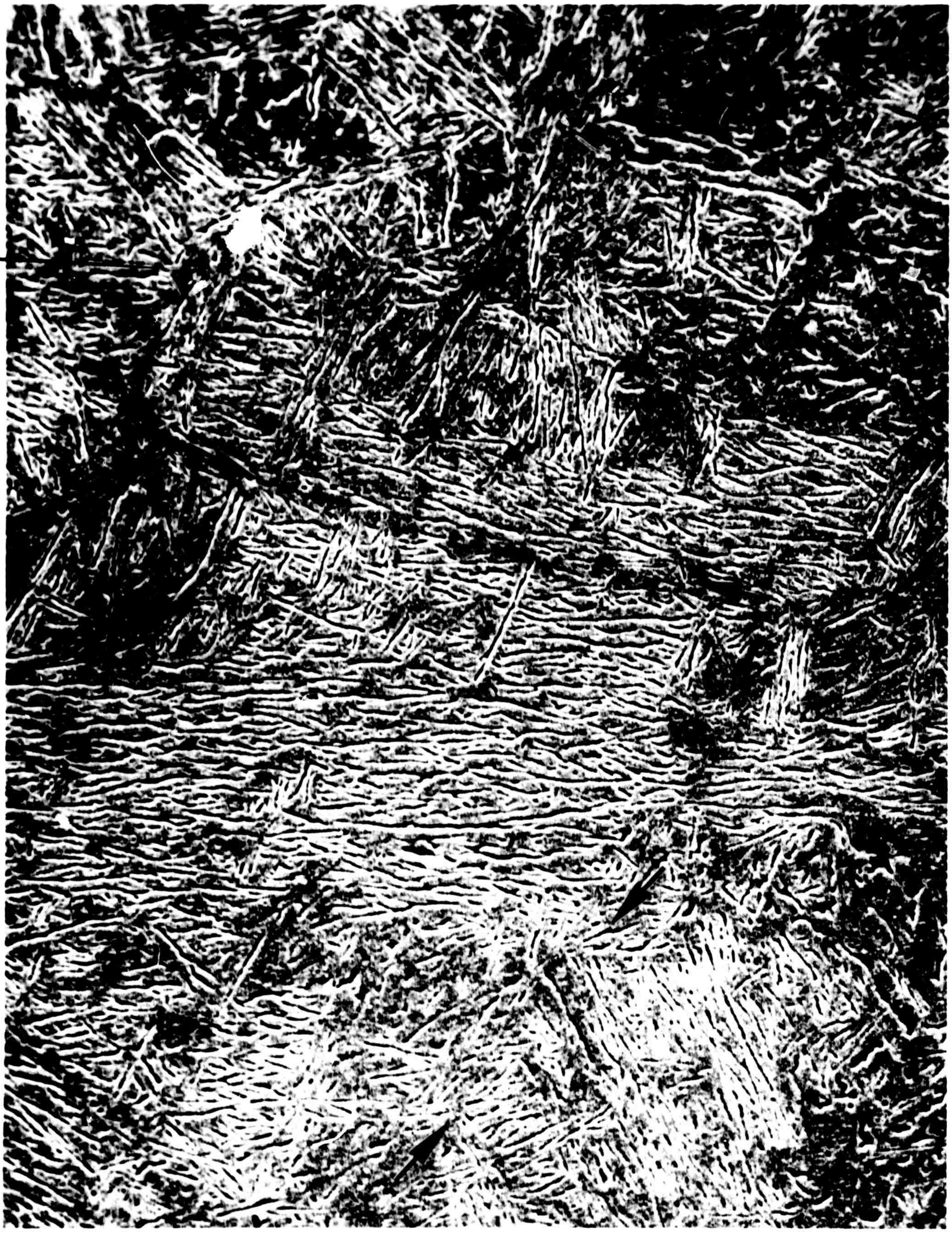

Figure 4 4340M: undeformed tempered martensite austenitized 1 hr at 1480°F and water quenched. Arrows point to new austenite grain boundaries between the blocks of aligned ferrite lathes. Scanning microscope picture (X920).

Figure 5 4340M: undeformed tempered martensite austenitized 1 hr at 1480°F. Arrows point to austenite grain boundary. Extraction replica (X12,000).

Figure 6 4340M: tempered 1 hr at 1275°F, cold reduced 50%, austenitized 1 hr at 1480°F, and water quenched. Blocky ferrite lies at the boundaries of fine, equiaxed austenite grains. Extraction replica (X12,000).

Figure 7 4340M: tempered 1 hr at 1275°F, cold reduced 50%, and austenitized 1 hr at 1525°F. Undissolved carbides remain. Extraction replica (X12,000).

Figure 8 4340M: tempered 1 hr at 1275°F, cold reduced 50%, and austenitized 1 hr at 1550°F. Few undissolved carbides remain. Extraction replica (X12,000).

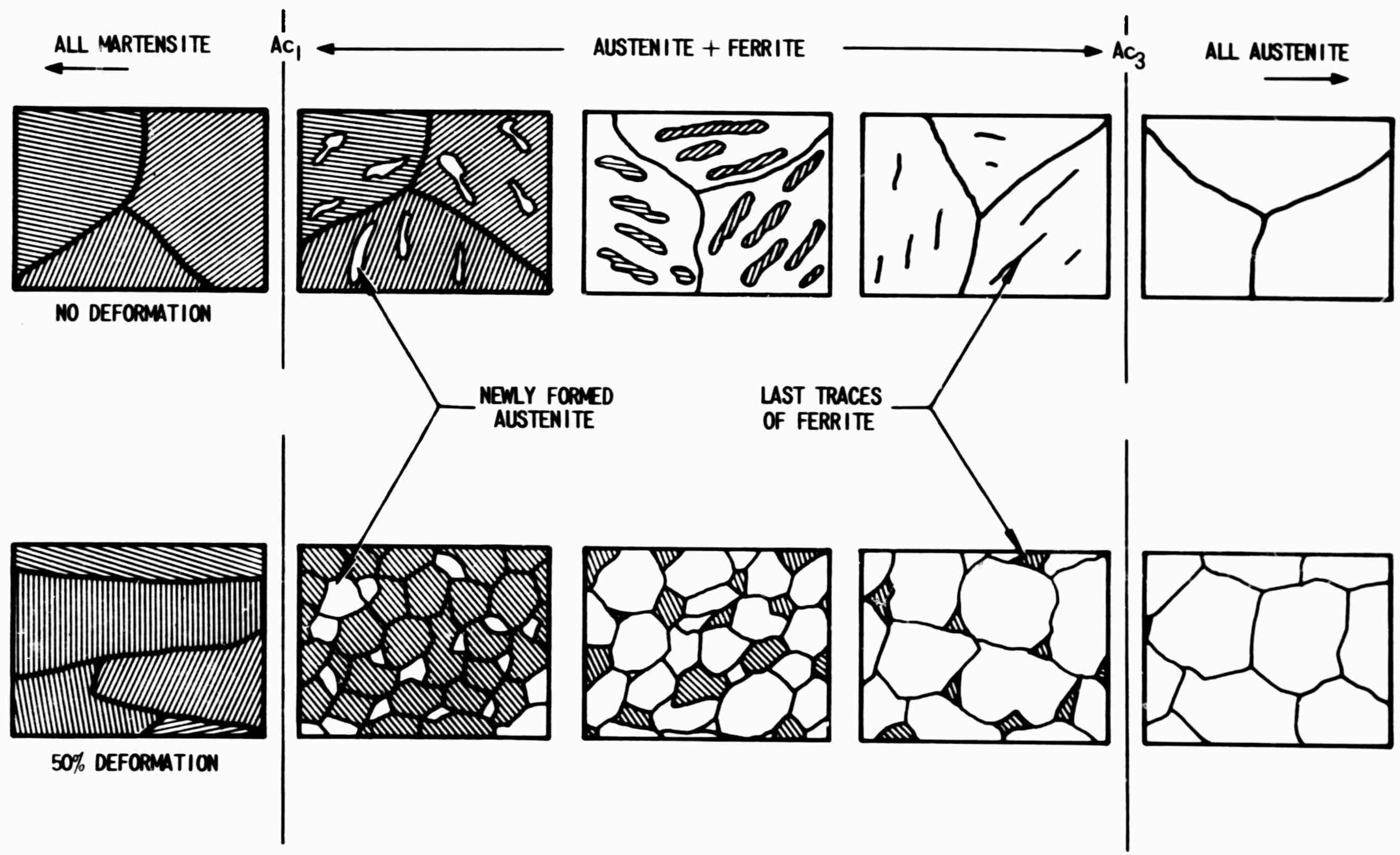

Figure 9 Schematic representation of microstructural changes that occur duing austenitizing of deformed and undeformed tempered martensite in 4340M.

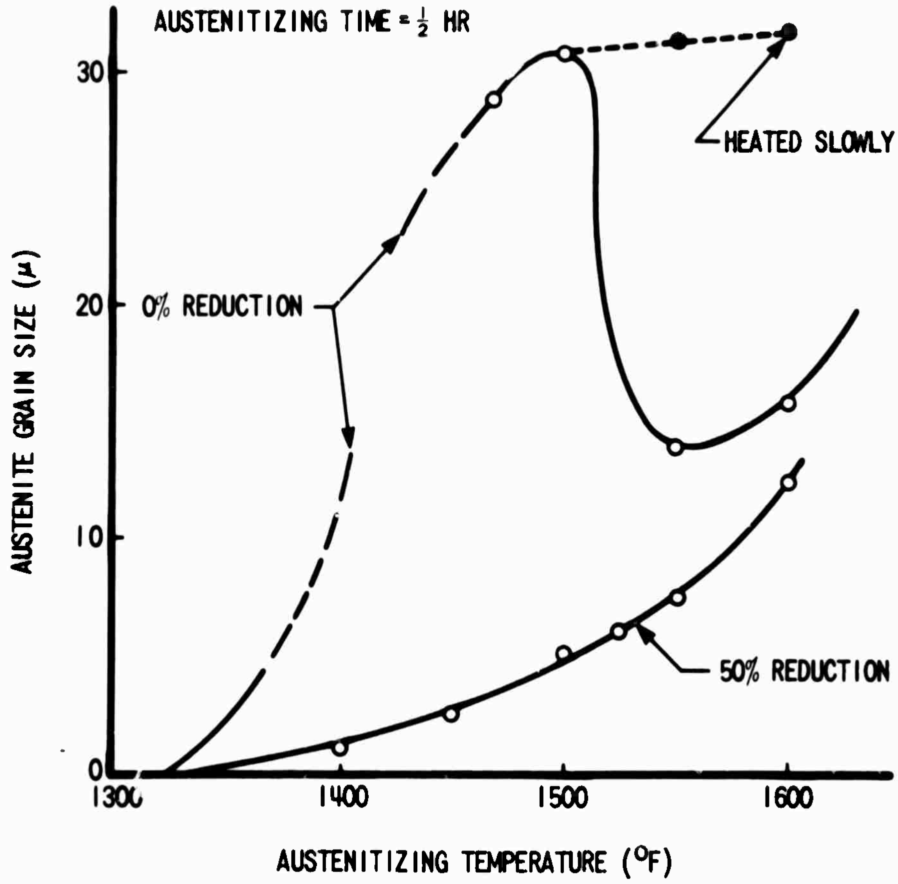

Figure 10 Effect of austenitizing temperature on austenite grain size of deformed and undeformed tempered martensite in 4340M. Drop in grain size at 1550°F and 1600°F is not observed in slowly heated specimens.

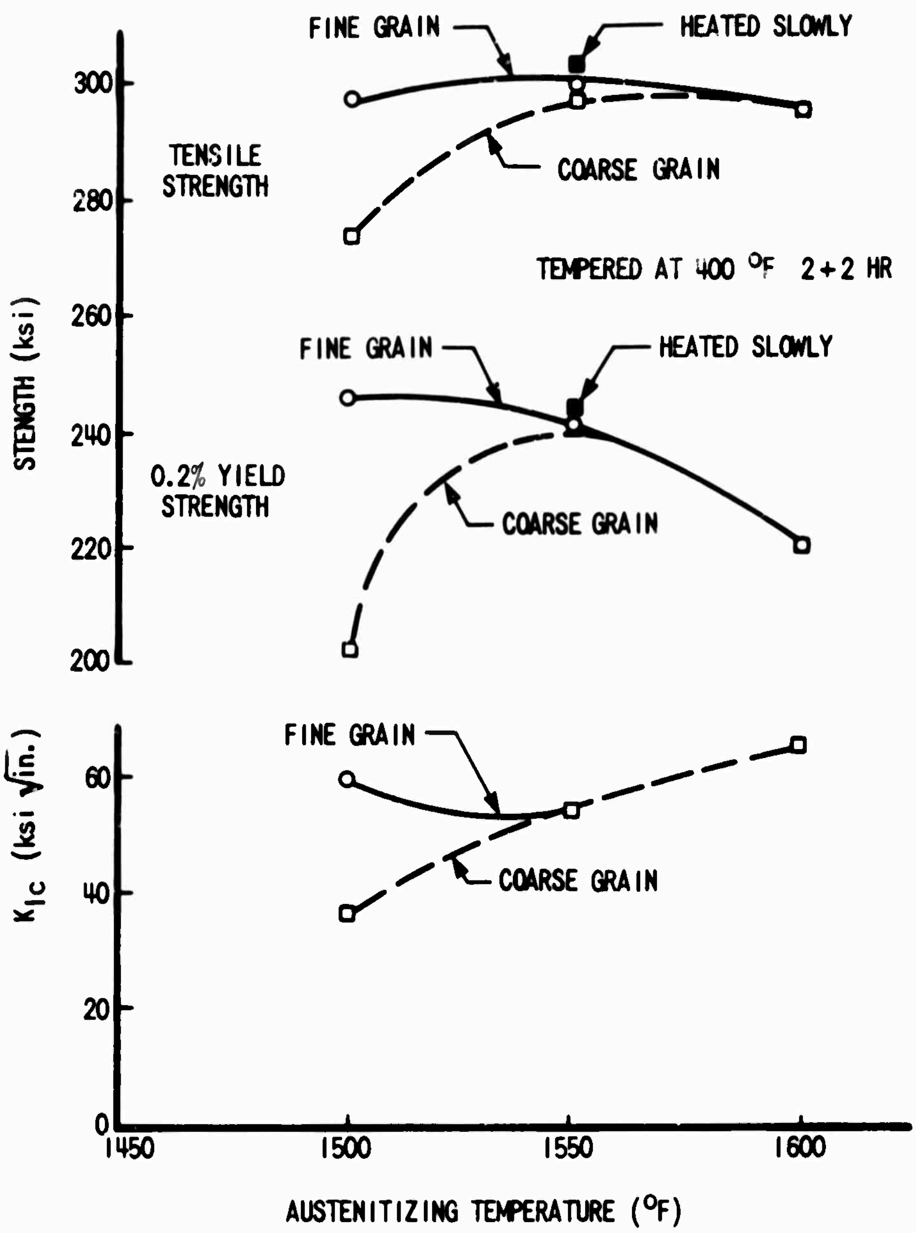

Figure 11 Strength and toughness of fine- and coarse-grained 4340M tempered at 400°F.

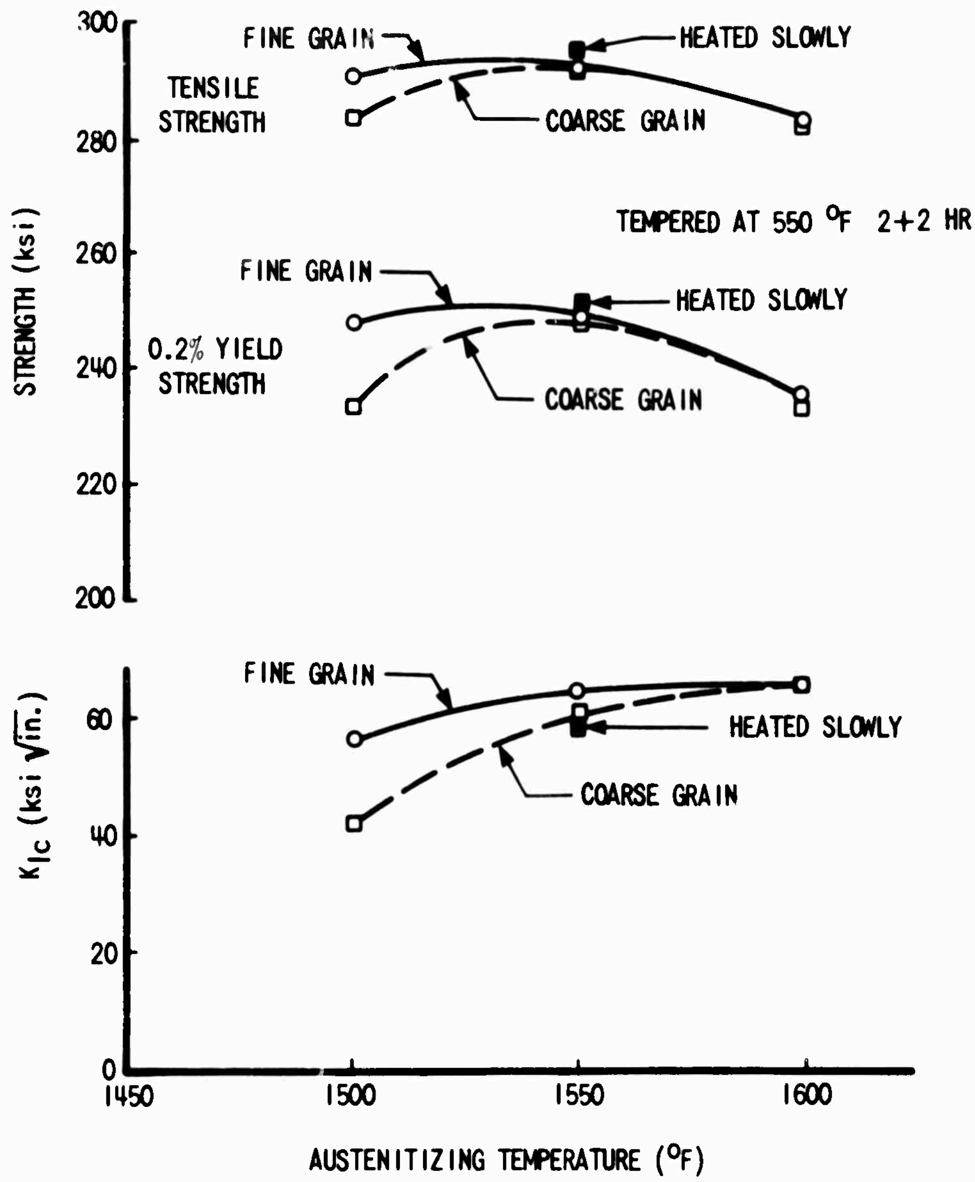

Figure 12 Strength and toughness of fine- and coarse-grained 4340M tempered at 550°F.

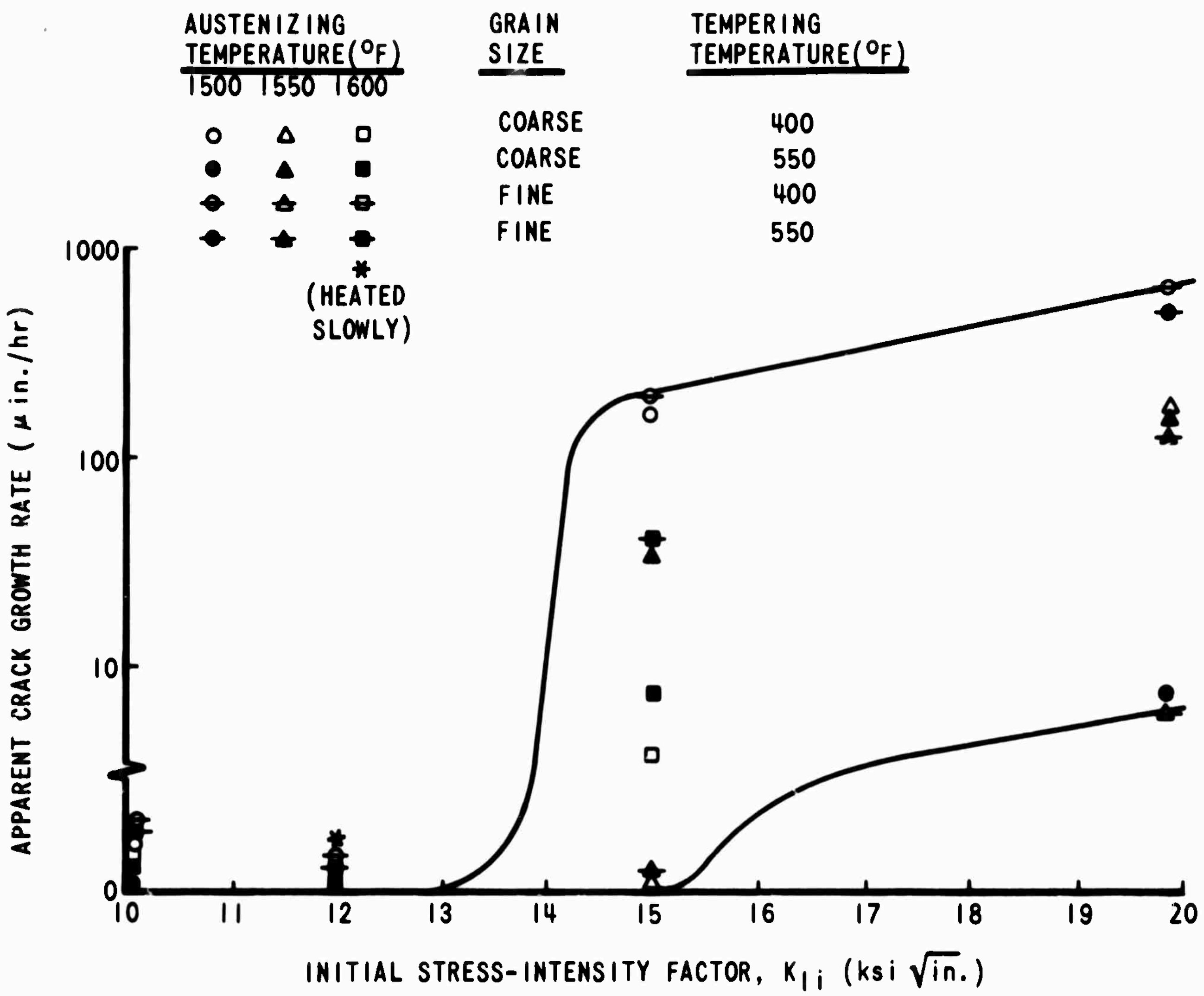

Figure 13 Apparent crack growth rate in 3.5% NaCl solution in fine- and coarse-grained 4340M tempered at 400°F and 500°F. The stress-corrosion threshold is not appreciably affected by either grain size or tempering temperature.

Figure 14 Intergranular stress-corrosion fracture path in fine-grained 4340M austenitized 1/2 hr at 1500°F and tempered 2 + 2 hr at 550°F. Scanning microscope picture (X2,000).

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13. ABSTRACT

A new grain refinement technique involving grain boundary pinning by deformation voids has been investigated in 4340M steel. Significant grain refinement is observed in deformed specimens at all temperatures between Ac_1 and $50^{o}F$ above Ac_3. In a narrow temperature region just above Ac_3, grain refinement produces an increase in strength and toughness but no increase in stress-corrosion threshold. It is concluded that to take full advantage of the new grain refinement process, compositional modifications of 4340M type steels are required.

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